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Editorial

Concrete Structures: Latest Advances and Prospects for a Sustainable Future

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1. Introduction

Along with structural steel, structural concrete is probably one of the most widely used construction materials worldwide for building construction and civil engineering infrastructures. Concrete is manufactured from cement and water and a mixture of fine and coarse aggregates that is suitably adapted in a wide range of regional variations. As a result, concrete does not really depend on strategic materials for its use, which has probably been the main reason for its pre-eminence as a building material in industrialized countries from the last quarter of the 19th century up to the present day. While it offers an attractive set of undoubted advantages, such as the one just mentioned, its essential ingredient, cement, has become its Achilles' heel in the recent two decades. The architecture and engineering sectors must face the challenge of anthropogenic climate change.

Cement is responsible for between 5% and 8% of the annual global anthropogenic CO_2 emissions [1], which are mainly concentrated in the production of clinker. Moreover, from 2015 to 2022, the ratio of tonnes of CO_2 emitted per tonne of cement (global average), far from decreasing, has increased by 7%, standing at a historical record of 0.58 tonnes of CO_2 per tonne of cement [2]. It should not be forgotten that structural concrete needs to work together with steel to configure reinforced concrete and pre-stressed concrete structures. Therefore, the targets of the global Sustainable Development Goals [3] challenge the concrete construction sector to enforce a responsible and rational consumption of cement and steel in order to control their environmental impact as well as to maximize recycling and recirculation possibilities. For obvious reasons, this aim must be achieved without compromising the structural safety or resilience of our infrastructures and urban services and dwellings.

In contrast to what happened with the MDGs (Millennium Development Goals) program [4] that preceded the 2030 Agenda, the research and engineering community today enjoys a scenario of great technological progress in information processing, in the training of database processing algorithms, and in artificial intelligence in general [5]. Likewise, the methods and tools for life cycle assessment (LCA) analysis in building and civil engineering projects now have a much more advanced degree of formalization and implementation than two decades ago. The same is true for topics such as the progressive replacement of Portland cement by other solutions that began to be proposed and researched in the late 1990s, such as geopolymer cements [6,7] and recycled concrete [8,9], the knowledge of which has progressed considerably in the recent 25 years. All this represents a powerful support when it comes to managing the challenges faced by the world of structural concrete for a sustainable future.

As noted in Angst [10], the downside of any subject that has been thoroughly and meticulously researched and developed over so many decades is that concepts and ideas have become deeply ingrained in the minds of those involved. Thus, after 150 years of growth in the concrete sector, there is a risk that the scientific community will show a tendency to take certain aspects of concrete for granted, rather than questioning alternative ideas or the quality of their impact on the sustainable development of society, the economy, and technology. This is the main reason that justifies this Special Issue, entitled "Concrete Structures: Latest Advances and Prospects for a Sustainable Future", that we present here.

2. An Overview of Published Articles

Cement-based materials are the most widely adopted construction materials worldwide [11] and their applications date back many centuries. In contribution 1, the authors propose a deep and detailed survey on the chemistry of cement. The paper highlights the fundamental role of water in the hydration reactions in ordinary Portland cement. The evolution of the chemical composition and the formation of pores are examined. The authors particularly discuss the evolution from plastic paste to the set material during the setting time and the development of the mechanical properties after the hardening step. Water plays an important role in these mechanical properties as it affects the porosity of cement. Moreover, a review of the use of recycled materials in the production of new green cement-based materials is also presented with the aim of summarizing new developments and trends in this construction field, such as the adoption of smart inorganic materials, which can represent a possible tool in the challenge of self-healing and health monitoring of structures.

The design of retrofitting interventions on existing structures firstly requires the acquisition of structural materials' mechanical properties. Among these properties, concrete compressive strength plays a key role in the vulnerability analysis of reinforced concrete (r.c.) structures, but the 'classical' approaches require the execution of destructive tests, which are time-consuming, expensive, invasive, and often difficult to execute for logistical reasons. Alternative approaches make use of non-destructive tests, which are more versatile and quicker than destructive tests; as such, contribution 2 investigates the use of the rebound hammer test. Attention is devoted to the evaluation of the accuracy of the strength assessment related to the choice of the conversion model that correlates the rebound index to the concrete compressive strength. The paper compares several conversion models calibrated by means of a great number of combinations of the data acquired in an experimental investigation on an existing r.c. building. The numerical analysis reveals that the values of coefficients of those analytical models manifest a high variability. The constants of the relationships between the coefficients of these models were established by utilizing regression analysis, and the influence of the coefficients of variation of both concrete strength and rebound index on the results of the calibration procedure were estimated.

Another topic involved in the design of r.c. structures is the realisation of foundations. Among such structural elements, the design of pile foundations, retaining walls, and submerged foundations is investigated in contribution 3. In detail, the paper explores the soil–structure interfacial shear strength and the frictional parameters, which represent key parameters in the design procedure for these foundations. The evaluation of these parameters is investigated considering several types of soils, such as silty sand, medium-coarse sand, clay, and sandstone. In detail, the authors investigate the influence of soil moisture content, normal stress, and interface filling material on the shear parameters of the soil–concrete interface. To this end, large-scale direct shear test apparatus is realised, and different soil–concrete conditions are tested. The results of the experimental campaign highlight that, for stable shear stress, the shear displacement of the sandy soil is smaller than that of clayey soil. Moreover, as the soil moisture content increases, the friction angle of the clayey soil–concrete interface decreases rapidly. The authors show that in the case of medium-coarse sand and the concrete interface, the friction coefficient is greater than that of the silty sand–concrete interface. Moreover, for a fixed moisture content, the authors discuss the friction angle when the soil–concrete interface is filled with a thin layer of sandy soil or silt.

The success of cement-based composites in civil structures is mainly due to their versatility, durability, and cost, even if they require rigorous design procedures to overcome their weak tensile strength and low ductility. In view of improving the mechanical behaviour of these materials, fibre-reinforced cement mortar (FRCM) has been developed by adding chopped fibres in cement composites. In detail, two kinds of FRCMs are available: mono fibre-reinforced cement mortar (MFRCM), which is characterised by the use of only one type of fibre, and hybrid fibre-reinforced cement mortar (HyFRCM), which is obtained by adopting two or more different fibres. These materials are commonly used in during reparations. Consequently, a deep knowledge of their mechanical behaviour represents an important objective in the management of r.c. structures. In contribution 4, the authors study the flexural performance, compressive strength, and impact resistance of both MFRCMs, containing only steel fibre (SF) or carbon fibre (CF), and hybrid fibre-reinforced cement mortar (HyFRCM) containing different combinations of SF and CF. The main aim of the study was to select the optimal fibre combination able to guarantee the required mechanical performance compared with plain mortar. The authors highlighted that the use of MFRCM or HyFRCM improves flexural performance in comparison to plain mortar. Moreover, they estimated how to choose the percentages of SF and CF to acquire higher values of impact resistance or flexural toughness, showing that the adoption of HyFRCM can improve the energy absorption capacity compared with MFRCM.

In recent decades, several multi-storey reinforced concrete buildings have been built with pillars on the ground floor for parking purposes, while the upper floors were reserved for residential use and were realised by inserting unreinforced masonry infills. However, earthquake events highlighted that this configuration is responsible for a different distribution of stiffness along the height of the structure, which is characterised by high stiffness on the upper floors and a "soft-storey" on the ground level. Therefore, during earthquakes, the ground floor columns and/or shear walls are subjected to an increased earthquake demand. However, usually, these structural elements are not designed to withstand such forces; thus, plastic hinges become damaged and in these scenarios, which can lead to a partial or total collapse of the building. This behaviour can also be observed when there is an irregular distribution of infills in plan, which can be responsible for torsional responses and an increase in vulnerability. In contribution 5, the authors investigate a retrofitting intervention aimed to increase the stiffness, shear capacity, and ductility of ground floors in irregular buildings. The intervention involves the realisation of reinforced concrete infills within existing r.c. frames located on the ground level after the execution of r.c. jacketing of the chosen frames. The retrofitting intervention is investigated by performing experimental tests on six 1/3-scaled single-story one-bay r.c. frames subjected to cyclic horizontal forces. The study highlights the key role played by the connections between the r.c. infill and the surrounding jacketed frame realised by means of steel ties. The paper also discusses a numerical procedure for the estimation of the behaviour of retrofitted frames, considering the nonlinearities related to the RC infill, RC frame, steel ties, and mechanisms at the interface. The numerical procedure is also validated by means of the experimental results and may be utilized for design purposes.

In the design of r.c. structures in seismic prone zones, building codes [12–14] introduce a factor whose symbol and name vary for each code but whose introduction is aimed to reduce the full elastic demand in a structure to bring the structure closer to the inelastic range. The evaluation of such a factor represents an important step in the seismic design of structures and conditions as well as energy dissipation requirements. The selection of this factor depends on the main features of the structure and may be quite difficult for buildings with irregularities. On the other hand, recently, due to architectural purposes, several buildings have been built with irregular distributions in their plans and/or elevations. Therefore, the selection of an appropriate reduction factor is quite difficult due to the torsional effects connected to the complexity of a structure. This topic is investigated in contribution 6, which proposed a method for the selection of this factor based on resilience aspects. The method was tested by selecting an appropriate factor value for a high-rise

L-shaped building, considering both unidirectional and bidirectional loading at two design levels. The performed analysis considered several factors, such as building performance level and ductility demand, and its findings can be applied to irregular buildings.

Several structures need to be strengthened for adoption to actual performance requirements. Several approaches have been proposed, but this topic is still highly debated due to the development of new materials and associated design procedures. The actual codes do not provide clear prescriptions for the design of these interventions. This circumstance inevitably affects their wide application in practice. In contribution 7, the authors investigated this research topic by studying the bearing capacity of reinforced concrete beams on shear without internal shear reinforcement. They proposed a method for the design of a strengthening intervention with a fibre-reinforced cementitious matrix (FRCM). The design procedure considered, as a new factor, the loading level at which strengthening occurs. In this regard, the authors discussed the test results of six samples and proposed a procedure for the assessment of a reinforcement system's additional carrying capacity. A new coefficient was introduced, which was able to consider the change in the load level and the related variation in the reinforcement effect. The proposed method has good accuracy and may be easily adopted in practical design.

Contribution 8 investigates the use of a machine learning approach for assessing the subsurface tensile strength of cementitious composites containing waste granite powder. The latest one derived from the crushing or cutting of granite rocks and the use of this material to produce cement composites may contribute to a reduction in the effects of these waste products on the environment and a reduction in the use of cement. However, the calibration of components for obtaining prescribed mechanical properties remains to be investigated. In this field, the availability of non-destructive procedures may represent a powerful tool to predict the effects of components on a product's properties. Indeed, the most commonly adopted procedures make use of destructive tests, which are time-consuming and costly, not only for the execution of these tests but due to the effect they have on the environment. In this view, the adoption of non-destructive tests may represent a good alternative, such as the Schmidt hammer. However, to improve the accuracy of their prediction, artificial neural networks were adopted by the authors. In detail, the authors proposed to combine the results of non-destructive tests with artificial neural networks, allowing them to estimate subsurface tensile strength for different compositions of cementitious composite elements containing granite powder. Different artificial neural networks were tested by the authors, and their performances were compared.

Concrete is one of the most adopted construction materials all over the world due to its several advantages. However, it requires the use of natural resources for its realisation. It has been estimated that the concrete industry produces 14 billion cubic meters of concrete every year [15], to which approximately 8% of the global emissions of carbon dioxide are connected. Thus, a new challenge of the research is the development of strategies capable of reducing the level of harmful emissions for environmental purposes. A promising approach is to replace conventional cement ingredients with waste materials that are also advantageous for reducing waste and improving their management. Moreover, they may also represent a quite promising approach for developing countries, and contributions 9 and 10 deal with this topic.

Contribution 9 discusses a procedure to prepare so-called 'green concrete', i.e., a geopolymer, and cement mortars using mineral wool waste. In the study, durability tests were performed to estimate the relationship between the amount of mineral wool and the flexural and compressive strength of mortars with the aim of determining if the immobilisation of mineral wool in the geopolymer allows to reduce the leaching of phenol and formaldehyde emissions to the environment. Moreover, the authors highlighted that the use of the highest cement-to-wool content ratio increases compressive strength. Moreover, geopolymer mortars show better flexural strength compared to cement mortars. The authors proved that immobilization of the wool in the geopolymer allowed them to significantly reduce phenol and formaldehyde leaching.

Contribution 10 investigated the effects of a partial replacement of ordinary Portland cement with cow dung ash (CDA) in mortar mixes. The authors evaluated the changes on workability, water absorption, bulk density, compressive strength, homogeneity, surface attack resistance, thermal decomposition, and mineralogical composition. The study highlighted that as the percentage of CDA content increased over the 5%, the mortar's workability reduced and affected its density and compressive strength.

An important topic in the field of the maintenance and management of r.c. structures is the knowledge of the effects of some commonly adopted maintenance tasks on the durability of structures and on their safety level. In contribution 11, the authors dealt with this topic and investigated the effects of the use of de-icing salts in bridge decks on the corrosion of steel rebars and on post-tensioning elements. The paper highlighted that in concrete sensitive to an aggregate–alkali reaction, internal stresses may occur, thus causing a high number of cracks. These cracks, in conjunction with the lack of an adequate waterproof treatment, may cause chlorides to enter from de-icing salts. Therefore, the macroscopic appearance of a brittle fracture of transverse reinforcements can be observed. These pathologies may affect the safety level of bridges and the costs of structural maintenance in a bridge deck, along with the use of de-icing salts. The issue is also explored by analysing a bridge, which was repaired in 2020. The execution of high-performance waterproof treatments during the construction phases can play a key role in avoiding the evolution of the previously mentioned pathologies and can reduce their effects on structural safety. Existing structures that are not waterproof are also discussed.

Contemporary architecture is characterised by complex geometrical features, whose realisation requires structural materials able to be adapted to such geometries and with high strengths. Based on these demands, self-compacting high-strength cement-based materials can represent an ideal solution. In contribution 12, this topic is investigated with the aim of identifying models able to optimise the performance of self-compacting mortars. The study focuses on fresh state properties and strength development. The authors used a statistical response surface methodology, which was adopted for the analysis of a database that included a total of thirty formulations of self-compacting mortars with four quantitative input variables. The authors tested the performance of the models by assessing the coefficient of determination related to the D-Flow, T-Funnel, compressive strength development after 24 h, and compressive strength development after 28 h. The estimated coefficients confirmed that the models displayed good performance, proving that this approach has practical potential.

Several authors [16,17] investigated the application of artificial intelligence techniques on the assessment of concrete mixtures' strength, a goal which may have immediate and significant returns in practical applications. In contribution 13, the authors developed a new procedural binary particle swarm optimization algorithm to predict the density and compressive strength values of concrete mixtures. The procedure used within the study outlined various fresh state properties, such as slump, temperature, and grade of cement, of several ready-mix concrete plants to predict the density and compressive strength of concrete mixtures. The results showed that the proposed algorithm achieved better performance in speed and accuracy in comparison to the binary particle swarm algorithm.

Contribution 14 dealt with the assessment of r.c. structures' seismic vulnerability. Several actual building codes [13,18,19] prescribe, among other procedures, the execution of experimental tests to estimate the mechanical properties of concrete and steel, whose number depends on the desired knowledge levels. Three different knowledge levels are proposed by the codes, and three different values of a confidence factor are provided. This factor is utilized to reduce the mean values of experimentally evaluated mechanical strengths, which are then adopted for the numerical assessment of structural safety. Even if the number of prescribed tests is fixed for each knowledge level, different technicians in charge of structural evaluations can make different choices regarding the structural elements that need to be tested for obtaining a prescribed level of knowledge. The authors, using a Monte Carlo approach, numerically simulated the acquisition of experimental strengths related to different choices of test locations, which were then utilized to assess the structural safety level of a reinforced concrete framed structure built in the 1960s in Italy. A huge number of possible choices for each knowledge level were considered. It is worth pointing out that different testing locations may lead researchers to assess different values of mechanical properties, which is based on what safety indexes are obtained. Therefore, the probability distributions of the estimated safety levels were evaluated, and the probability of unsuccessful safety estimations was discussed for the three knowledge levels considered in the Italian technical codes and the Eurocodes.

3. Conclusions

The contributions included in this Special Issue can be classified into four groups. Contributions 1, 9, 10, and 11 deal with advances in the knowledge of cement and concrete chemistry. They delve deeper into their understanding and improve techniques for predicting the working life of infrastructures. Moreover, they incorporate new materials that have a positive impact on sustainable development. Contributions 2, 3, 4, 7, and 14 present experimental studies for characterizing the mechanical behaviour of structural concrete and present quantitative results. Similarly, contributions 5 and 6 also describe experimental and numerical tests for the evaluation of the structural behaviour of concrete, but they focus specifically on the effect of seismic action, with the aim of providing conclusions that will make it possible to achieve resilient building designs that do not compromise the safety of users. Finally, contributions 8, 12, and 13 make use of the latest advances in technology for the treatment of large databases. Additionally, they utilize the application of artificial intelligence algorithms to improve the design of experiments or to optimize concrete dosage parameters and estimate mechanical properties.

To summarize the conclusions drawn from these four groups of papers, we would like to highlight the following:

- Despite being responsible for a remarkable proportion of anthropogenic CO_2 emissions, cement (as a construction material) is backed by a vast knowledge and technology. We cannot ignore the amount of effort that has been put into its research over several decades. This research is essential not only for the design of new and environmentally innovative civil engineering infrastructures, but also for the maintenance and eventual repair of an enormous heritage of buildings, bridges, waterworks, etc., that were built during the 20th century and are still in use. Cement shows great potential and synergy for use with recycled materials for sustainable development. In fact, this Special Issue presents two examples of the use of mineral wool waste as a component for geopolymer and cement-based materials and the use of cow dung ash as an additive to cement. In the first study, resin-impregnated mineral wool fibres were successfully immobilized, significantly reducing formaldehyde leaching into the environment and demonstrating the potential of wool in geopolymer mortars for ecological building materials. In the second example, it was found that while cow dung ash could potentially meet the ASTM requirements for cement, its incorporation affects the workability, water absorption, and compressive strength of mortar mixes. Nevertheless, substituting up to 10% of OPC with CDA shows promise for sustainable mortar production. These research efforts underscore the complexity of building materials and the need for sustainable and environmentally friendly practices in the construction industry. They advocate innovative approaches such as the use of recycled materials, supplementary cementitious materials, and effective preservation strategies to address environmental concerns and ensure the longevity and safety of infrastructure.
- The evaluation of the structural safety of concrete buildings and infrastructure involves a wide range of disciplines and techniques that are constantly evolving. These include an adequate understanding of the soil–foundation interaction, which sometimes requires in-service intervention to improve the interface properties of varying soil moisture contents; the use of fibre-reinforced polymers and fibre-reinforced cementi-

tious matrices for various purposes, such as structural retrofitting of existing structures; the importance of using appropriate assessment analyses to validate the safety indexes of existing buildings, which may require a non-linear approach in combination with a sensitivity analysis to deal with the inherent uncertainties present in the input data; and, finally, the importance of the different locations of non-destructive test results within the same existing structure when using them for structural analysis, with an example that estimates the safety levels in a reinforced concrete moment resisting frame built in the 1960s by means of Monte Carlo simulations, considering different sets of experimental data.

- In the specific case of the seismic assessment of existing reinforced concrete buildings, the papers in this Special Issue demonstrate the power of the numerical analysis tools and methods available today as well as the development of innovative retrofit solutions. On the one hand, structural concrete offers the possibility of seismically retrofitting vulnerable existing structures by using reinforced concrete auxiliary structures and infills to enclose and strengthen them. On the other hand, aesthetic considerations often compromise the seismic safety of new structures, which lose symmetry and may exhibit torsional movements during an earthquake, thus challenging the structural assessment via response reduction factors. This Special Issue contains two papers that successfully address these issues, considering the required resilience of the designs, i.e., whether they are new or retrofitted. However, the papers also note that the standards applied in different countries make it difficult to generalize conclusions due to the different regional parameters that characterize earthquakes.
- Finally, machine learning tools are being applied to classical problems in concrete technology, such as predicting the properties of fresh and hardened conventional and self-compacting concrete mixes as well as the effects of adding waste materials. Artificial intelligence algorithms can be developed (such as the new Procedural Binary Particle Swarm Optimization method presented in one of the papers) and subsequently trained to provide accurate estimates of concrete properties, making them highly useful for their speed, accuracy, and low cost. This pioneering research advances our understanding of statistical methods in the field of civil engineering and construction materials. Artificial intelligence is therefore particularly relevant to the development of advanced, sustainable, and environmentally friendly cement-based products. There are still some limitations that need to be addressed before machine learning tools can be generalized for common practice—such as field tests, experimental verification, more comprehensive sets of mechanical properties—but the successful exploration of the proposed models further clarifies a roadmap for future explorations, with the potential to reduce production costs, limit the environmental impact, and improve the technical performance of mortars and concretes.

Conflicts of Interest: The authors declare no conflicts of interest.

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